

## LASER COMMUNICATIONS

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### Abstract

Ballistic Missile Defense Organization (BMDO) is developing advanced greater than 1 Gigabit per second data rate, anti-jam, low probability of intercept laser communication crosslinks between satellites and among Theater Missile Defense (TMD) and National Missile Defense (NMD) communications networks on the ground and in the air. Technology efforts are on-going in the following areas: ultra-stable laser sources, wide field of view acquisition and tracking, novel beam steering concepts, spatially incoherent transmitter arrays, extremely high bandwidth receiver systems and novel networking concepts. The program has successfully demonstrated an operational laser communications system in the presence of platform motion experienced in high altitude aircraft at a range of 150 km. Future plans include a 1998 demonstration of a satellite-to-ground communication link.

### Introduction

For extremely high data rate communications between satellites, aircraft, or the ground in situations where cloud interference can be avoided or does not exist, laser communications can offer significant advantages over radio frequency (RF) communications in terms of achievable data rate, size, weight, and power requirements. These issues are especially important for data transfer from smaller unmanned aerial vehicles with large sensor capabilities. The large amounts of raw data from the sensors must not encounter any bottlenecks during the transfer to a processing station. As shown in Figure 1, after processing on a lower flying larger aircraft, the reduced data can be transmitted to the ground via RF which has tolerance of cloud interference that may occur closer to the ground.

Lasercom's advantages over radio frequency can be primarily attributed to its capability to produce a highly focused beam of energy, enabling more signal to reach the receiver for a given amount of transmitted power. The divergences of the

laser beams used in this lasercom system are on the order of 100  $\mu$ rad. However, the disadvantage to these narrow beams is that they need to be pointed very accurately, well within their divergence for maximum efficiency. Having the gimbaled system installed on an aircraft further complicates the issue, as motion and vibration can impart pointing error for the outgoing beams, causing them to miss the distant lasercom terminal. Development of a large field of view acquisition and tracking system based on the high performance of atomic line filters (ALF) has enabled demonstrations of the lasercom system at distances up to 150 km in broad daylight. ALF's require the use of ultra wavelength-stable laser sources, also developed under this program. Many experiments have been performed to test the effectiveness of a novel az/slant gimbal system and multiple laser transmit apertures at varying spatial separations. Another experiment performed involved mounting a lasercom terminal to a motion base platform that mimics the motion and vibration encountered on an actual high flying aircraft. Critical tests of the lasercom tracking system followed, and target acquisition using data from an inertial navigation unit (INU) processor was performed. The transmission of Common Data Link data at 274 Mbit/sec over the lasercom link was accomplished as part of the bi-directional, dual optical channel link demonstration. Digitized video and repeating bit pattern sources have been used to demonstrate the laser link at 1.13 Gbit/sec. Figure 2 shows a functional milestone diagram of lasercom demonstrations. Preliminary air to ground tests have been performed and will continue, while an air to air system is being fabricated to accommodate this demonstration. A spin-off application for lasercom has been developed in the form of a short range, hand held lasercom binocular and position finder.

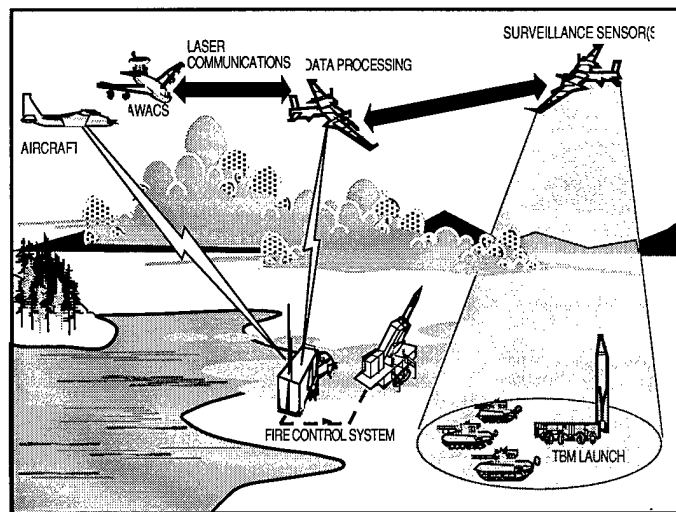
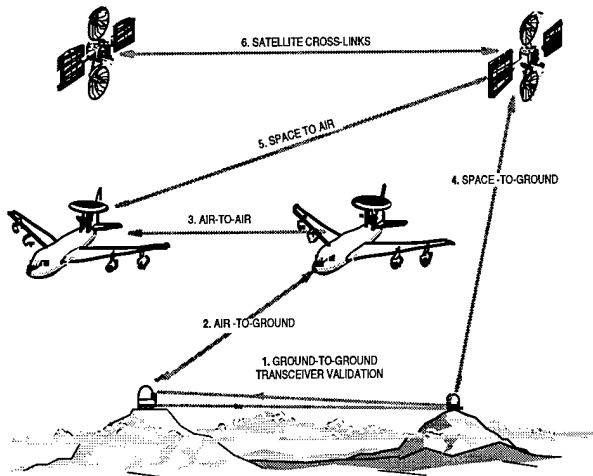


Figure 1. High Data Rate Laser Communications Links for Theater Air Operations. High traffic, long range links would use laser communications, while shorter range, low traffic links (which might encounter poor visibility conditions) would use radio frequency communications.



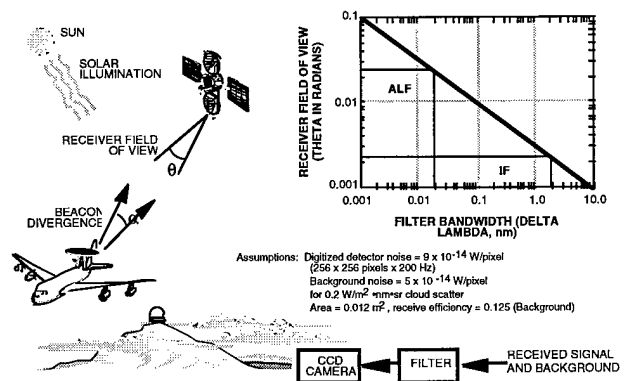
**Figure 2.** Functional Lasercom Demonstration Milestone Program. Experimental links which should be demonstrated include ground-to-ground, ground-to-air, air-to-space, and space-to-space.

### Advanced Component Technologies

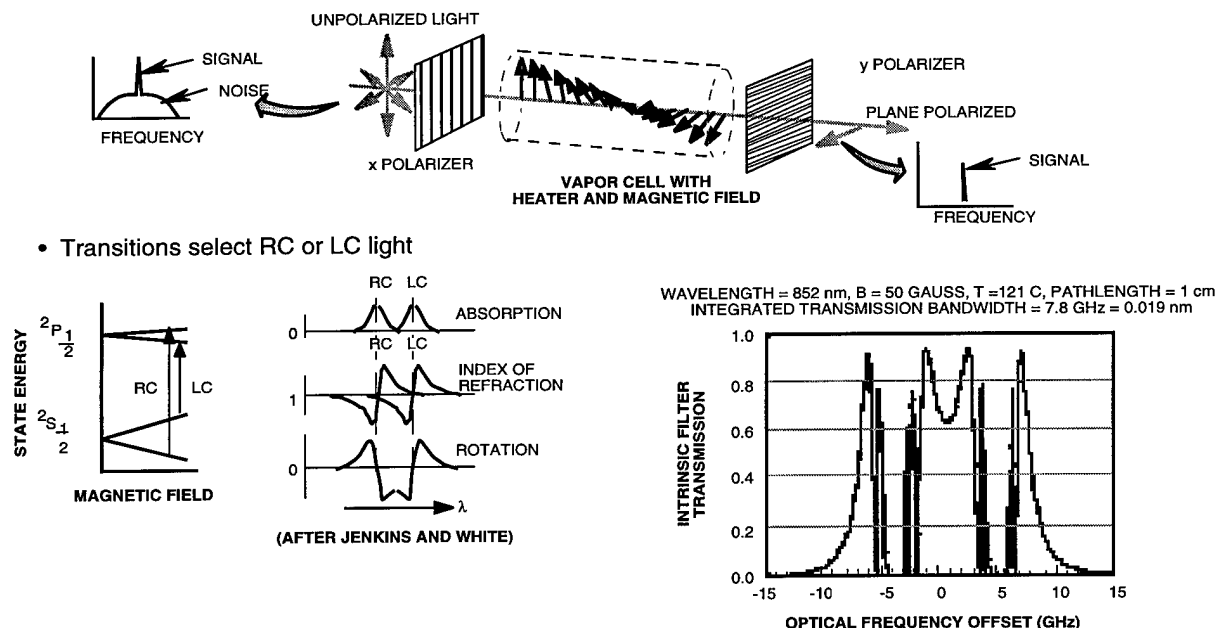
One of the issues associated with laser communications is potential interference from background solar radiation scattering off of optical elements, or reflected from the earth or clouds. For a high data rate communications channel, an interference filter with a bandwidth of 10 nm can be used to bring background light noise down to the level of detector noise because the detector field of view for background light can be very small, and the needed signal strength is already quite large due to the high data rate. On the other hand, acquisition of a laser beacon to initiate a lasercom link requires much better background light rejection. The reason is that a satellite or aircraft has limited accuracy knowledge of what direction in space it is pointing at a given time, so that to ensure fast acquisition a receiver field of view of 1 degree or more is desirable. If the earth is in the field of view of the receiver, such as for a satellite to aircraft or ground link, the background light intensity will be significant. A system design goal is to increase the acquisition camera's per pixel field of view until the background light per pixel is equivalent to the detector noise for that pixel. Since the same receiver element will be used for coarse tracking, spatial as well as temporal fluctuations in the background light can cause inaccuracies in the centroid calculation, meaning that the maximum background light intensity, rather than its square root, is the amount to contend with in the system model. The atomic line filter permits a much larger per pixel field of view because of its ultra narrow optical passband. Because we would also like the acquisition beacon (which the Lasercom transceiver locks on to initiate a link) to have as wide a divergence as possible to minimize scanning times, we should choose an optical filter in the

receiver for which the background noise is less than the detector noise for the desired field of view. Figure 3 shows a link acquisition scenario for which there is significant background light, and shows the receiver field of view as a function of filter bandwidth for which the background light noise equals half the detector noise. After digitization, the noise equivalent power of the camera is  $9 \times 10^{-14}$  Watts/pixel. The background light is assumed to be  $0.2 \text{ W/m}^2 \cdot \text{nm} \cdot \text{sr}$ , with a telescope aperture of  $0.012 \text{ m}^2$  and a telescope and filter throughput of 0.125 for background light. (Transmission is 0.25 for the polarized beacon signal). From the figure we can see that a filter bandwidth of 0.02 nm is required for an acquisition field of view of 20 mrad to minimize beacon scanning. This filter bandwidth can not be achieved using an interference filter, and thus we have incorporated an extremely narrow band atomic line filter in our system. An additional advantage of using such a narrow band filter is that telescope baffling requirements against solar scatter are greatly reduced, and a much shorter, more compact low f/number telescope design can be used.

Operational principles of the atomic line filter, which we call a Faraday filter<sup>1,2</sup> because it relies on the Faraday effect in an atomic vapor, can be understood by reference to figure 4. Crossed polarizers serve to block out background light with a rejection ratio better than  $10^{-5}$ . We use high transmission Polarcor polarizers which have a transmission of higher than 95%. Because these polarizers only work over a limited wavelength region in the infrared, a broadband interference filter is used in conjunction with the Faraday filter. Between the polarizers an atomic vapor (in this case cesium) in a magnetic field rotates the polarization of the beacon laser signal of interest by  $90^\circ$ , while leaving other wavelengths unrotated, and thus blocked by the polarizers. The path of the transmitted light is unaffected, so spatial information is maintained.



**Figure 3.** Fast Acquisition Requires Superior Background Light Rejection. The achievable acquisition field of view is a strong function of the optical filter bandwidth.



**Figure 4.** Operational Principles and Transmission Spectrum for Faraday Atomic Line Filter. Crossed polarizers block background light, while the polarization of the signal wavelength is rotated, allowing it to pass through the filter. The transmission bandwidth is temperature and magnetic field dependent, and has been adjusted to accommodate a large range of satellite Doppler shifts.

Polarization rotation is due to the separation in optical absorption frequencies for right and left circularly polarized light in the magnetic field due to the Zeeman effect. The index of refraction of the vapor near an absorption is different from 1, and the absorption separation causes the index to be different for right and left circular polarization at a given frequency, and thus those polarizations travel through the vapor with a different phase velocity. The effect of this is to cause a frequency dependent rotation in the polarization of the incoming linearly polarized light which only occurs near the atomic absorption. Transmission through the filter is maximum where the polarization is  $90^\circ$ ,  $270^\circ$ , etc., provided that the frequency is far enough away from the atomic resonance not to be absorbed. A filter transmission spectrum at 852 nm for cesium in a 1 cm pathlength cell at a temperature of  $121^\circ\text{C}$  and in a magnetic field of 50 gauss is shown in the figure. This filter has an equivalent noise bandwidth of 0.019 nm and the parameters have been chosen to give a transmission passband wide enough to accommodate intersatellite Doppler shifts. (Much narrower transmission features are possible). The features at -4 and +5 GHz in the figure are the locations of the two hyperfine absorptions in cesium, and the high transmission occurs in the wings of these absorptions.<sup>3</sup>

High power diode lasers are available which match the 852 nm wavelength of the cesium atomic line filter. We have developed techniques to control the wavelength of the laser so it matches the filter transmission spectrum. A previous technique

used optical feedback, and incorporated a small yet complete atomic line filter. A small amount of feedback from the output coupler through the filter served to stabilize the laser at the peak transmission wavelength of the filter over a fairly broad range of diode laser drive currents. The development of high power, single mode distributed Bragg reflector (DBR) diode lasers has simplified the beacon laser wavelength locking solution because the DBR lasers are continuously tunable in wavelength. Previous diode lasers used for our application exhibited "mode hopping" which are abrupt changes in wavelength as temperature and/or current is varied. This characteristic did not lend itself well to the simple electrical and temperature adjusting locking scheme we now implement. Locking the laser wavelength to the atomic transition of Cesium is accomplished by sampling a small amount of light from the laser and passing it through a glass atomic vapor cell. There are two sharp drops in optical transmission through the cell due to atomic absorption when the wavelength of the light is scanned smoothly, now possible by scanning the current to DBR lasers. When the absorption is detected using a photodiode, the two values of current are stored in the control processor. Then the laser drive current is set to the value halfway between those sensed at absorption, producing a laser output wavelength that passes through the receiver's ALF. Because the laser current is digitally controlled, slight adjustments can be programmed in to accommodate Doppler shifts encountered between terminals mounted on Low Earth

Orbit satellites and the ground. Higher laser output powers and less optical loss produce a factor of three to five times greater output power than the previous scheme, to 150 mW CW. Thus, slightly larger divergences can be designed into the system, up to 6 mrad for some applications, further lowering the acquisition or scanning time.

### Trex Communications Lasercom System Description

The primary Trex Comm lasercom program that has been funded for the past eight years has incorporated these technologies into two terminals, each consisting of a gimbaled optical assembly and electronics rack.

#### Optical head assembly

There are various optical apertures for transmitting and receiving the optical signals on the gimbal structure. Figure 5 shows one of two current generation lasercom gimbaled optical head assemblies built by Trex Communications. A 5.4 inch diameter Schmidt-Cassegrain receive telescope collects the incoming light, splits the high speed comm and wavelength locked beacon signals and focuses them onto their respective detectors. For the transmit signals, there are two wavelength locked beacon diode lasers and four 150 mW peak communications diode lasers, two of which are left hand circularly polarized and two that are right hand circularly polarized. This provides two independent optical channels for high speed data, each channel capable of over 500 Mbit/sec for a combined link data rate of over 1 Gbit/sec. The comm lasers have approximately 100  $\mu$ rad of divergence, while the beacon divergences are 2 mrad. All of the apertures are co-aligned and move together when the gimbal is moved. Due to the additional complexity involved, a fast steering mirror was not implemented in this system.

The key behind the operation of the wide field of view acquisition system is the atomic line Faraday filter, which is placed in front of the Dalsa 256 x 256 pixel, 225 Hz frame rate tracking CCD camera. The Faraday filter optical bandwidth is 0.019 nm near 852 nm, with in band transmission of 70% (given polarized signal light) and out of band rejection of better than  $10^{-5}$ . This requires that the beacon laser is locked to the transmission peak of the filter, as described earlier.

The mechanical structure of the gimbal and various critical optical mounts are fabricated from carbon graphite fiber and epoxy composite for a high stiffness to weight ratio and low coefficient of thermal expansion to maintain optical co-alignment and divergences. Direct drive DC motors and a two axis angular rate gyro are used to drive and stabilize the gimbal. Micro-lensed comm and beacon laser diodes are used to simplify optical design and increase efficiency.

#### Electronics

The electronics associated with this testbed system have been chosen to maximize versatility and utilize available commercial off the shelf hardware. There are two VME type card cages. The upper VME cage houses electronics for beacon control, comm laser drive, and digitized video conversion. The lower VME cage has the tracking and gimbal control cards, consisting of the i960 DSP, Dalsa CCD camera drive, CCD threshold and storage, Canon optical encoder interface, motor amplifier, analog filter and gyro interface, and Radisys 486 imbedded PC for user and low speed comm interface. There are rack mount units that perform the digitized video multiplexing to 560 Mbit/sec and demultiplexing before D/A conversion for one optical channel. Another rack mount unit provides a repeating bit pattern at 570 Mbit/sec and has a bit pattern receiver for testing the second optical channel.

Additional work has been done to interface to the CDL system's INU processor so that it can provide azimuth and elevation pointing angles based on ephemeris data to the lasercom system for initial pointing prior to optical acquisition and tracking. This is important if the motion base is slewing and the optical signal is interrupted, as may occur on an actual aircraft if for example the wing breaks the optical link momentarily. The lasercom system disregards the INU pointing information if the system is optically tracking the signal from the other terminal.

An analog filter and gyro interface circuit board was built to accommodate the stabilization and tracking loop without sampling or digitization error and delay. Although the loop gain and frequency parameters could not be changed in software, the design is quite simple and fairly straightforward to tune and is providing trouble free use.

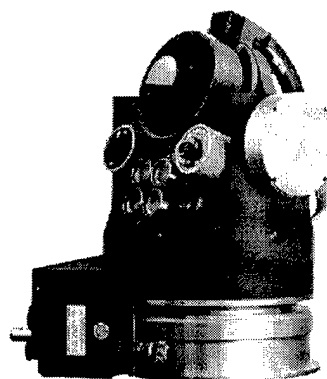


Figure 5

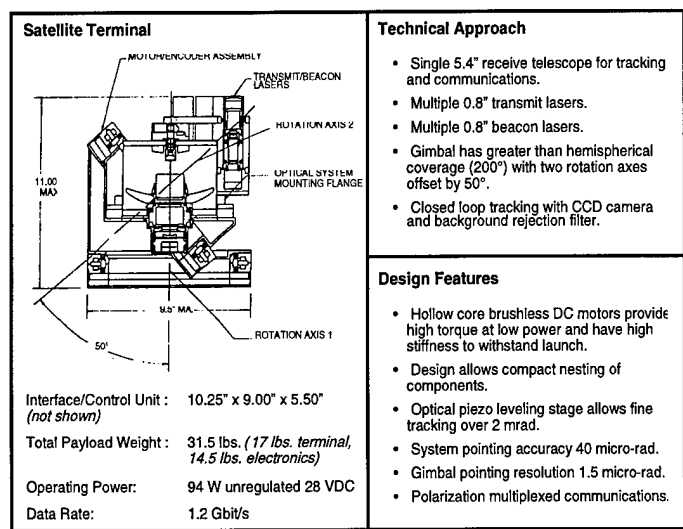
- Bistatic transceiver
- Nine boresighted optical axes
- Full duplex operation
- Common gimbal
- $\pm 170^\circ$  azimuth range
- $+50$  to  $-10^\circ$  elevation range
- Previously interfaced to P3-A inertial navigator
- Previously interfaced to common data link
- Currently interfaced to Boeing Airborne Surveillance Testbed
- Boresighted diagnostic viewing camera

### Astroterra Corporation STRV-II Satellite Terminal

Astroterra Corporation of San Diego, CA is providing a lasercom terminal for space flight testing aboard the STRV-II (Space Technology Research Vehicle) due to launch in late 1998. Hardware has been delivered to Jet Propulsion Laboratories in mid 1997 for integration onto the satellite. Funding has been provided by BMDO and NASA for this ground breaking experiment, the first ever to attempt over 1 Gbit/sec data rates to and from an orbiting lasercom terminal. This will be accomplished with a design that incorporates many innovative concepts, of them a novel az/slant gimbal design. Figure 6 shows a cutaway view of the gimbal and orientation of the axis. The overall system architecture is compatible with the existing Trex Communications lasercom terminals in that it utilizes circular polarization optical multiplexing, similar laser wavelengths and direct on/off keying up to 600 Mbit/sec. Link ranges to a dedicated ground terminal will be 800 to 1800 km, with encounter durations of 4.5 to 10 minutes.<sup>4</sup>

#### Novel beam steering concept

Because overall size and weight requirements for the lasercom terminal and associated electronics onboard the spacecraft were very restrictive, the design of the gimbal incorporates non orthogonal axis. There are several advantages to this concept, primarily in structural stiffness and in reduced overall size. The bearing structures are quite large in diameter (9 inch O.D.), and incorporates Farrand Controls Inductosyn™ rotary position transducers and frameless hollow core brushless DC motors of similar diameter. These combined assemblies are oriented at 50 degrees to each other, with the optical apertures nested into the slant ring at 50 degrees also. This enables a greater than hemispherical field of regard while enabling a stiff



**Figure 6.** Feature of the Space Qualifiable Lasercom Terminal. Summary of the key features including weight, power, size, and field of regard.

structure because significant masses are nested within the bearing assemblies and the structure that holds the bearing rings to each other can be triangulated. The overall envelope volume is cylindrical, 9.5 inches in diameter and 11 inches tall, yet holds a receive telescope 5.4 inches in diameter, 10 0.8 inch diameter apertures for transmit lasers and an auxiliary camera, and various circuit boards and sensors. The large diameter motors require less power to accelerate the assembly because of the greater radial distance from the axis, and the large diameter encoders more easily obtain the required 1.5 microradian resolution. The coordinate transforms required for precisely pointing the optical axis in a given direction have been derived and incorporated into the control and tracking software.

Other achievements include reaching the power and weight goals for the system of 94 watts peak and 31.5 pounds. Recent vibration tests have been successful in that the multiple transmit lasers remained aligned and although thermal vacuum tests have turned up a few small problems, they have been handled. Custom high speed, high efficiency quad laser drivers were developed and are employed in the system.

#### Risk Reduction Experiments

##### Spatially incoherent transmitter arrays

Lasercom links for terrestrial applications are subject to atmospheric effects, namely scintillation which causes constructive and destructive interference across the wavefront of the coherent laser light from a single source. This is due to turbulence of the air along the propagation path, and appears as light and dark patches across the illuminated spot. The size of a typical "dark spot" depends on the pathlength and atmospheric conditions, primarily wind velocity, and has been approximately calculated to be 14 inches for a 170 km path.<sup>5</sup> A possible solution for mitigating the effects of scintillation is to transmit multiple output laser beams from apertures that are spatially separated by some minimum distance. AstroTerra has fabricated a test fixture comprised of 16 co-aligned collimated 780 nm diode laser transmitters that can be individually enabled and relocated with respect to each other. A single receive aperture was used to collect the light at distances of 1.2 and 10.4 km, depending on the elevation angle above the horizon.. The receiver was an 8 inch Celestron telescope with various sized masks to test the effectiveness of aperture averaging. Tests were performed at various times of the day and night, with varying numbers of lasers enabled in an 18 inch diameter circular configuration. The received signal from the photodetector was digitized at 10 kHz and normalized for comparison.

The results indicate that increasing the number of transmit apertures does indeed help decrease the depth and duration of the signal fades<sup>6</sup>, as shown in figure 7. Thus, a terrestrial system would benefit from multiple output apertures not only from a redundancy standpoint, but also a performance one.

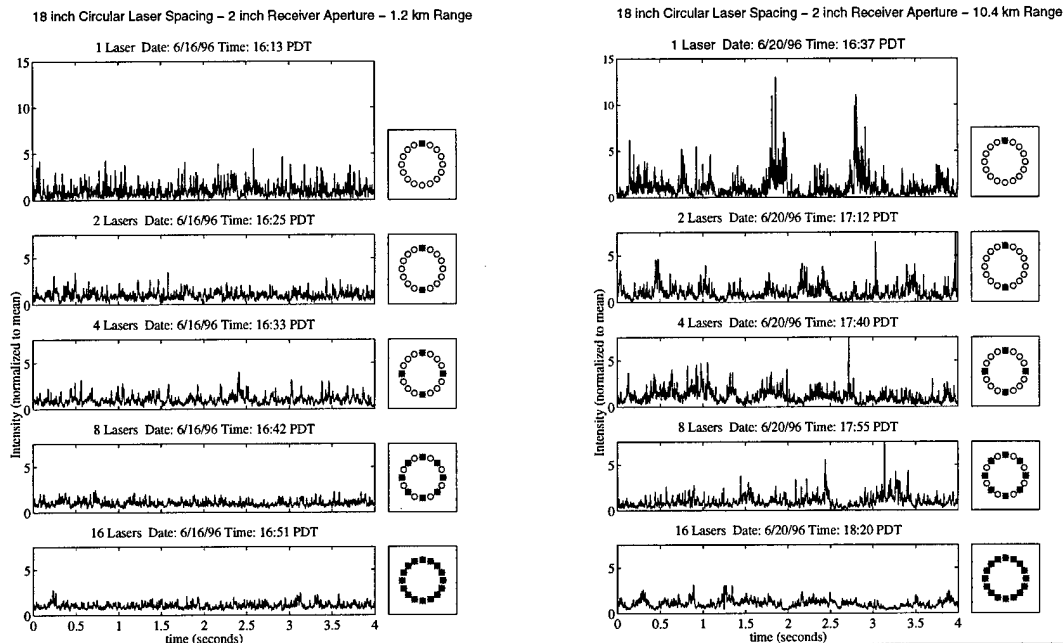


Figure 7a (left). Time series plots for the 18" circular spacing at the 1.2 km range.

Figure 7b (right). Time series plots for the 18" circular spacing at the 10.4 km range.

### Advanced Technology Demonstrations

#### 150 km experiment using aircraft motion simulator<sup>7</sup>

##### Site description and experiment architecture

There were many traits that were desirable in a test location. Two sites needed to be separated by about 150 km, with a clear line of sight unobstructed by trees, mountains, or structures. Power and telephone hookups are important, as well as an indoor room in which the equipment can be safely stored and operated. Lower attenuation at high elevations would permit the longest possible links, and prevent the earth's curvature from interfering with the line of sight. The locations that were chosen are Haleakala on the island of Maui (ThermoTrex has employees working on other experiments at the summit), and the National Oceanic and Atmospheric Administration (NOAA) aerosol measurement building near the summit of Mauna Loa on the island of Hawaii. Haleakala is at 9700 feet elevation, and the site at Mauna Loa is at 11,300 feet. A preliminary test of the lasercom system was performed in May 1995 at which time, according to the NOAA measurements, there were fewer particulates in the air than when the lasercom/motion platform tests were conducted in September 1995. May also proved to be a time of the year when there was less fog and cloud cover on Haleakala, making the September tests difficult to complete.

The actual link tests took place at various times of the day in an attempt to avoid foul weather. After trying at various times throughout consecutive nights, and after the weather

pattern settled down, it appeared that operating from about 4 am to 10 am would be best. There were still indications that the link quality was adversely affected by the increase in particulates in the air, as compared to the May tests. Weather conditions during the tests ranged from 5°C and heavy winds at 4 am to almost 30°C, calm and sunny at 12 noon.

The motion base platform, CDL downlink transceiver, and the "aircraft" lasercom terminal were located on the Haleakala side because the access roads were better, more room for equipment existed, and more power was available. The Mauna Loa site housed a "ground" lasercom terminal on a stationary base, support equipment, and the CDL data transceiver. The critical direction for high speed data flow is from the "aircraft" to the "ground", which is also the most difficult in terms of the tracking requirements because the transmitted comm laser beams have less divergence than the comm receiver's field of view. The tracking system must remain pointed towards the "ground" terminal to within 40  $\mu$ rad ( $\pm 20$   $\mu$ rad peak from center).

##### Hardware description

The largest piece of equipment is the motion base platform. It consists of six hydraulic legs oriented at angles between the floor base and the moving table. See figure 8. It can provide pitch, roll, and yaw motions and a limited amount of vertical piston motion. On top of this platform are three electromagnetic linear actuators oriented at right angles to each other, all attached to a single phenolic plate supported by

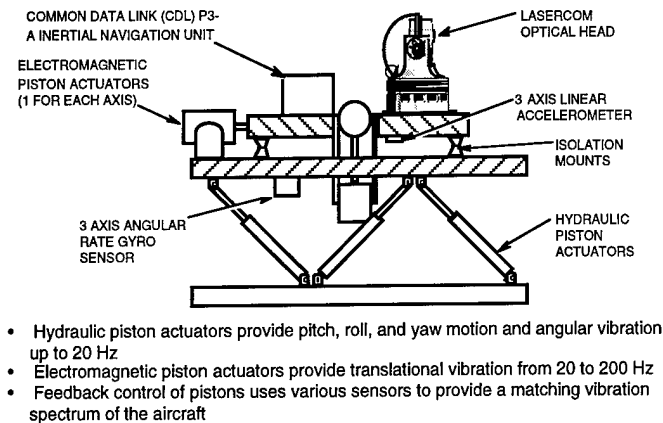


Figure 8. 150 km link experiment hardware - motion base.

isolation mounts. These linear actuators provide translational vibration motion with respect to the table of the hydraulic base. The hydraulic platform can provide a vibration spectrum of DC to 20 Hz, while the electromagnetic actuators can operate from 20 to 200 Hz. Note on figure 8 that there are motion sensors on each respective plate to enable feedback control and measurement of the actual platform vibration spectrum to verify its matching with the aircraft vibration spectrum.

The CDL inertial navigation unit is also mounted on the phenolic plate, and therefore detects the orientation of the lasercom base. The INU processing unit calculates its own location and, given a target "ground" location, calculates an azimuth and elevation angle for the "antenna" (as used with the RF CDL system). The ground location is input as the Mauna Loa location, and the azimuth and elevation angle commands are fed into the lasercom tracking processor via the user interface communications port for open loop pointing if the optical tracking signal is lost. The CDL data transceiver is also interfaced to one channel of the lasercom transceiver as previously described.

### Experiment

The dual channel, bi-directional capabilities of the lasercom system were tested during full vibration and a simulated 20° roll and 15° yaw maneuver of the motion platform. The simulated aircraft terminal on Haleakala sent two channels of high speed data. One channel was the CDL video data at 274 Mbps, the other was multiplexed uncompressed digitized video at 560 Mbps. The Mauna Loa terminal was simultaneously transmitting a 143 Mbps digitized video signal (the high speed video system suffered from a damaged oscillator which caused intermittent operation) on one channel, and a low data rate CDL audio link on the other channel. The bit error rate (BER) was difficult to estimate from the video display because of the effects of resynchronization delays of the video demultiplexer, which is not optimum for this type of frequent burst error data link. An estimate for the BER is approximately

$10^{-4}$  overall, with better than  $10^{-6}$  for the periods between signal dropouts due to atmospheric scintillation.

The tracking error was also difficult to measure because of the lack of a true reference from which to measure deviations in LOS pointing. Some data was taken using the actual received beacon signal centroid error. The incoming beacon signal centroid is compared to the camera center, and this error value is sent to the D/A converter and output as an analog signal that can be analyzed on an oscilloscope. This method showed tracking errors of approximately 110  $\mu$ rad peak in azimuth and 60  $\mu$ rad peak in elevation. These numbers are somewhat higher than what was measured in Salt Lake City at the preliminary motion base test primarily because of varying intensity of the received beacon signal in Hawaii which caused significant blooming in the CCD. Even though there was compensation in the software to accommodate this blooming, the algorithm was quite simple and still produced a perceived error on the order of 80  $\mu$ rad for large blooms.

### Aircraft to ground experiment<sup>8</sup>

The Boeing Airborne Surveillance Testbed (AST) is the first flight capable 767 built by Boeing and is now used for SSDC experiments. The lasercom experiment was "piggybacked" with a scheduled AST mission at White Sands Missile Range. After the early morning mission, the aircraft would refuel and fly to San Diego, where it would then fly a series of circles at a radius of 20 or 30 km at an altitude of 30,000 ft, centered on the ground lasercom terminal location. Slight modifications to the aircraft were made that included installation of an optical quality, 2 inch thick window that replaced one of the standard passenger windows near the front, right hand side of the aircraft. Another window was fitted with a plug that held four solid 2 1/4 inch retroreflectors. These would be in place for all testing, to determine if a single ground terminal retroreflected signal was sufficient to track the aircraft in the event that the air terminal became inoperable. A stand was made to mount the lasercom optical head in close proximity to the window, and includes a mounting surface wedge of about 14 degrees from horizontal to better accommodate a lookdown angle consistent with a 30,000 ft altitude, 20 km link to sea level. The ground location was the northeast corner of the parking lot at Trex Comm, located approximately 3 miles north of Miramar Naval Air Station. The ground terminal was leveled and calibrated to true North.

After the mission was complete in White Sands Missile Range, the AST landed in Roswell, NM, refueled, and headed for San Diego. 40 minutes from San Diego, a modem data link was established between the ground terminal and the AST and range information calculated by the ground lasercom terminal compared favorably with the aircraft navigation computer. Visual sighting of the aircraft con-trail occurred at about 200 km range, the weather in San Diego was clear and sunny. After the AST arrived and began its closer of two flight orbits, automatic acquisition was attempted with little success.

Because flight time was limited to two hours above San Diego, manual acquisition with automatic switch to optical tracking was attempted. Simultaneously, it was found that the aircraft roll motions were often times quite extensive, and the IRU data at a 1 Hz update rate was too latent for accurate open loop pointing of the air terminal, thus the air terminal was switched over to manual control also. Several times a large return signal was received at the aircraft, but the automatic switch over to optical tracking did not occur correctly. Too much received beacon laser power was suspected, so the 30 km range orbit was flown. Moments later, both terminals acquired each other and tracked for nearly a minute. Once again, the perceived amount of intensity fluctuation was minimal, even at the aircraft, but the beacon intensities were not quite optimum for the lowest amount of tracking error. A small dropout in the signal during a period of greater aircraft roll resulted in loss of lock. Beacon power had been fluctuating, and most likely dipped below threshold.

Despite two "blind spots" encountered during each orbit (due to the Sun and a miscalculated waypoint), there were three periods of full tracking, each lasting 40 to 50 seconds, at a range of 30 km and 30,000 ft. The INU data latency will now come under scrutiny and extensive aircraft roll motions and rates were observed, even when flying a steady, straight course. Atmospheric scintillation effects were qualitatively evaluated and determined to be less than those encountered in previous ground to ground long range links. The tracking system, given appropriate signal levels, performed well. The wavelength locked beacon lasers at times flickered or drifted off wavelength because they incorporated the old optical feedback method of wavelength locking. A new laboratory set up has been built that better simulates what the aircraft terminal encounters while tracking, which helped determine that the integration constant

limit in software was too low and caused a slight mispoint during tracking.

### Related Programs for Supporting Lasercom Technology Readiness

#### Air to air demonstration - DARO program

A new lasercom program is underway at Trex Communications that will produce two flight capable systems with turret mounted gimbals that will mount to two T-39 Sabreliner aircraft, and be directly traceable to integration onto various proposed unmanned aerial vehicles. The link range is from 50 to 500 km at an altitude of 38,000 feet. Goals of greater than 1 Gbps data transmission at bit error rates of less than  $10^{-6}$  are specified. A rendering of the system is shown in figure 9. The optical system is significantly different from the existing system in that there is a piezoelectric fast steering mirror that uses a separate narrow field of view (FOV) CCD camera running at 10 kHz frame rate to stabilize the outgoing 80  $\mu$ rad comm laser beams. Also, there is one wavelength locked 130 mW, 6 mrad divergence DBR laser for coarse tracking and one 180 mW, 340  $\mu$ rad divergence diode laser for fine tracking. A refractive separate aperture for the narrow FOV CCD is mounted and co-aligned to the wide FOV 5.4 inch input aperture. The wide FOV CCD sensor has an atomic line filter incorporated in the optical path, as well as a ferro-electric liquid crystal variable attenuator to accommodate the wide range in link distances.

The mechanical system design is also vastly different from the current lasercom gimbals. There is a small field of regard (FOR) flex pivot mounted inner gimbal that can move  $\pm 6$  degrees on two axis and provide better than 100  $\mu$ rad

#### TURRET ASSEMBLIES FOR INSTALLATION TO TWO T39 SABRELINERS

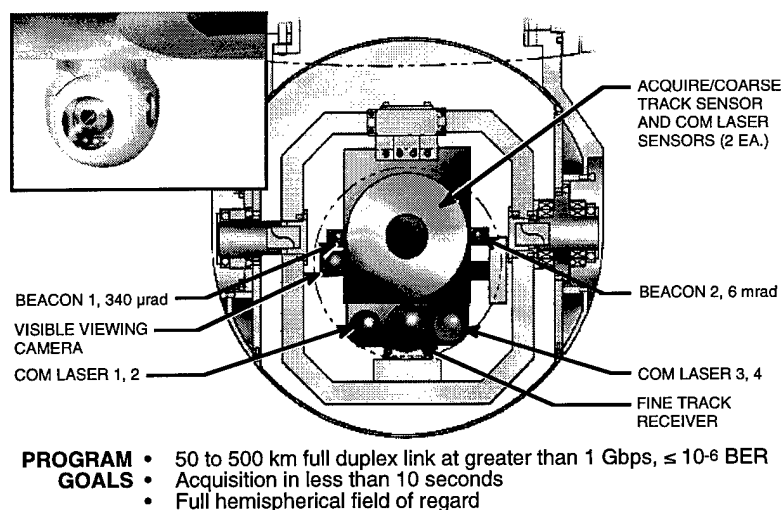


Figure 9



tracking ability for the communications avalanche photodetectors. It is rate gyro stabilized and controlled by the coarse tracking CCD running at 100 Hz. This inner gimbal is mounted inside an aircraft mounted two axis turret assembly that will provide low bandwidth coarse tracking capability with greater than hemispherical field of regard. A 700 Hz bandwidth piezoelectric steering mirror is mounted behind and slightly below the main telescope and reflects both the incoming narrow FOV beacon light and the four outgoing communications beams that have been polarization combined into two diffraction limited beams. The beams hit the mirror in three different spots to avoid backscatter issues. Graphite composites and invar will be used for critical optical assemblies for thermal stability, and the inside of the turret will be temperature controlled. Although this architecture is a radical departure from the current design, it will provide a level of performance and capability of tracking through zenith that is unobtainable in the previous systems.

Electronically, the data capabilities will be similar to the existing systems by utilizing optical polarization multiplexing to achieve greater than 1 Gbps. Two high speed fiber optic links will be implemented to reduce cable bulk from the inner gimbal to the electronics rack. System control is by a 100 MHz PowerPC RISC processor, CCD and tracking control utilizes Motorola C40 DSP VME mounted boards.

Completion of the systems is scheduled for March 1998, integration onto the aircraft during the following five months, and flight testing commencing August 1998.

#### Lasercom binoculars

A spin-off technology of the high data rate, long distance lasercom programs is the Lasercom Position Finding Binocular. Two full capability units have been fabricated and demonstrated to various military agencies. A compact (4.5 x 5 x 1.2 inch), lightweight (30 oz) bistatic lasercom transceiver is mounted to a commercial, off the shelf laser rangefinder, electronic compass and inclinometer made by Leica. A Trimble GPS unit is installed on the unit and all components are interfaced to a Trex Communications microprocessor control and memory unit (2 x 2.5 x 6 inches). Data from multiple targets is collected and stored in memory and can be transmitted to another lasercom binocular at data rates up to 400 kbit/sec. The data acquired is sufficient to enable a calculation of the actual position of the target. A lasercom audio link can be established between the two users, and work is progressing on the interface of a digital camera to the system to enable storage and transmission of an image in a matter of seconds with no resolution loss from compression. The link range is dependent on visibility, background light and scintillation conditions, and varies from 1.5 to 5 km. The Leica Vector laser rangefinder is subject to the same limitations, including the reflectivity of the target, operation has been observed to over 2 km with a 2 meter accuracy. The accuracy of the target calculation is dependent on the azimuth angle accuracy of the Vector and the GPS accuracy,

with preliminary tests indicating about 50 meter repeatability of the calculated location of a single target given 3 data sets each taken from 3 locations. The units are powered by 8 AA size batteries which can continuously run the units for about 4 hours at or slightly below room temperature. There is a thermoelectric cooler to coarsely control the temperature and wavelength of the laser diode.

The two units have undergone eye safety tests at the Army Center for Health Promotion and Preventive Medicine in Aberdeen, MD, and have been declared a Class 1 device that can be safely used with no laser safety restrictions.

A long term demonstration and evaluation program has begun at the U.S. Army Space Command in Colorado Springs, CO. The units will be used by trained army personnel during experiments conducted overseas. Other potential applications are being sought and investigated.

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